

Center for Lunar Origin and Evolution (CLOE)

The dramatic Apollo exploration of the Moon concluded in the early 1970s. Three fundamental scientific concepts emerged from this historic venture that profoundly changed our understanding of how objects like our Moon form and evolve. These ideas, as identified by the National Research Council's 2007 Space Studies Board report, "The Scientific Context for the Exploration of the Moon" (hereafter the *SSB Report*), are: (1) lunar origin by giant impact, (2) the existence of an early lunar magma ocean, and (3) the potential of an impact cataclysm at 3.9 billion years ago.

As often occurs with scientific discovery, however, these ideas have raised more questions than they have answered. For example:

- The Giant Impact theory proposes that the Moon formed as a result of a collision between the early Earth and a protoplanet half its diameter. While the idea that the Earth-Moon system owes its existence to a single, random event was initially viewed as radical, it is now believed that such large impacts were commonplace during the end stages of terrestrial planet formation. Sophisticated numerical models demonstrate that a giant impact can indeed produce a disk of rocky/vapor material orbiting the Earth. *However, we still do not know whether such a disk can evolve into the Moon that we see today.*
- The Late Heavy Bombardment (LHB) refers to a period about 4.0 to 3.8 billion years ago in which the large lunar basins with known ages were produced. The nature of the LHB is debated: one view is that the LHB marked the end of a steadily declining bombardment due to leftover remnants of planet accretion, while another proposes that the LHB was a short-lived "cataclysm" of dramatically increased impact rates onto the Moon. *We are still unable to observationally distinguish between these two fundamentally different histories of the solar system.*

To address these questions, we formed the *Center for Lunar Origin and Evolution (CLOE)*. Our focus is to investigate how our planetary system formed and evolved as well as determine how this information bears on the fundamental issues of the geophysical/geochemical make-up of the Moon and the lunar cratering record.

CLOE's first major theme is to explore the "***Formation of the Moon***". This involves modeling the giant impact on the proto-Earth, which produces an Earth-orbiting disk of molten rock and vapor, through to the end of the Moon's accumulation. The physics of the evolution of this disk controls the exchange of material between what will become the Moon and the Earth as well as any material loss to free space, thereby determining the compositional relationships between lunar and terrestrial materials. The coupled dynamical, thermal, and chemical evolution of the disk is largely uninvestigated, and it may – *or may not* – yield a Moon with a core/mantle/magma ocean structure and volatile content (including water) consistent with today's Moon. Our models will strive to validate, or invalidate, the widely accepted GI model through direct comparison with existing and future observational constraints.

CLOE's second major theme is to update the lunar impact chronology, which has changed little since post-Apollo analyses of radiometric ages. To do so, we will employ both bottom-up and top-down approaches.

For the former, we will determine new "***Observational Constraints on the Bombardment History of the Moon***". Here we will employ inventive techniques to deduce new physical constraints on impact rates throughout lunar history. Recent work analyzing terrestrial zircons has found intriguing evidence for a pre-LHB lull in the bombardment of the Earth-Moon system. This work will be extended to lunar and meteoritic samples to establish an early lunar bombardment chronology. We will also make new crater

counts of LHB-era and post-LHB-era terrains using an innovative method for analyzing lunar crater statistics, which will be applied to existing and upcoming lunar images.

For the latter, we will develop new “*Lunar Impact Rate Models*” from the pre-LHB era to the present. Our post-LHB impact rates will rely on new state-of-the-art dynamical models of the comet and asteroid populations as well as a novel method that can now date major asteroid break-ups and the asteroid showers they produce. To determine impact rates before and during the LHB, we will invoke a large-scale repositioning of the Jovian planets into the outer solar system’s disk of planetesimals as a trigger of a solar system-wide bombardment of asteroids and comets (as in the successfully predictive “Nice Model”; *e.g.*, Gomes *et al.* 2005, *Nature*). We will also assess the early, post-accretion impact rate due to planetesimals left over from planet formation.

CLOE consists of 12 interdisciplinary investigators from 5 institutions: Southwest Research Institute (SwRI, lead institution), University of Colorado, University of Arizona, Carnegie Institution, and the Lunar and Planetary Institute. CLOE also has national and international Collaborators, representing 7 additional institutions. CLOE will be directed by PI William Bottke, the Assistant Director of SwRI’s Department of Space Studies in Boulder, Colorado.

A key component of CLOE’s work will be to train the next generation of lunar scientists. This will be accomplished by integrating graduate and postdoctoral scientists in our work as well as by actively fostering undergraduate/graduate-level education in connection with the University of Colorado. CLOE is also enthusiastic about sharing the excitement of our lunar research through a cohesive education and public outreach (E/PO) program. Our central E/PO activities will be to 1) develop the next generation of lunar scientists in collaboration with the long-running Summer Science Program, Inc., which involves gifted high school students conducting authentic lunar science projects; 2) excite middle school aged children and families, with an emphasis on Hispanic and Native American audiences, about lunar science through LPI’s “Explore!” library program; and 3) partnering with high school students from the Denver School of Science and Technology to develop and maintain a web portal, infused with new media, describing CLOE research and sharing NLSI and NASA’s lunar science and exploration with the public.

The Moon is itself a fascinating object, but it is also recognized as the “cornerstone for deciphering the histories” of the other planets (to quote the *SSB Report*). Issues such as the Moon’s formation via a giant impact and the bombardment history of the Earth and Moon are not only scientifically fundamental but also generate a huge amount of public interest in lunar science. As Carl Sagan wrote in *Contact*, you would have to be made of wood not to feel awe before such questions.

Using lunar data, CLOE will probe the nature of the early Moon and Earth and explore how the architecture of the entire solar system may have evolved long after the planets first formed. We will focus the broad talents of our planetary physicists on issues central to the re-emergence of the Moon as the next step of NASA’s exploration program. CLOE’s PI, CoIs, and Collaborators have played central roles in developing new paradigms concerning lunar origin, the dynamical structure of the solar system, and the bombardment history of the terrestrial planets. We are eager to play a vital role within NLSI in advancing our understanding of the Moon and applying the results of lunar science and exploration to the wider planetary system.